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Review

Agricultural residue production and potentials for energy and materials services

Niclas Scott Bentsen [a,*], Claus Felby [a], Bo Jellesmark Thorsen [b]

[a] University of Copenhagen, Faculty of Science, Department of Geosciences and Natural Resource Management, Rolighedsvej 23, DK-1958 Frederiksberg C, Denmark
[b] University of Copenhagen, Faculty of Science, Department of Food and Resource Economics, Rolighedsvej 25, DK-1958 Frederiksberg C, Denmark

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ABSTRACT

Agricultural residues are potentially major contributors of resources for energy and material production. We provide regional and global estimates of the amount of residues from major crops and address the sources of uncertainty in the estimation of the amount of agricultural residues produced globally. Data and methods available currently limit the use of resource estimates for energy or production planning. We develop function based multipliers to estimate the global production of agricultural residues. The multipliers are applied to the production of the, on a global scale, six most important crops: barley, maize, rice, soybean, sugar cane and wheat in 227 countries and territories of the world. We find a global production of residues from these six crops of $3.7^{+1.3}_{-1.0}$ Pg dry matter yr^{-1}. North and South America, Eastern, South-Eastern and Southern Asia and Eastern Europe each produce more than 200 Tg yr^{-1}. The theoretical energy potential from the selected crop residues is estimated to 65 EJ yr^{-1} corresponding to 15% of the global primary energy consumption or 66% of the world's energy consumption for transport. Development towards high input agriculture can increase the global residue production by ~1.3 Pg dry matter yr^{-1}.

Contents

* Corresponding author. Tel.: +45 20 20 63 18.
E-mail address: nb@ign.ku.dk (N.S. Bentsen).

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Nomenclature

Y	crop yield (kg ha^{-1} yr^{-1})
RP	agricultural residue production (kg yr^{-1})
RPR	residue to product ratio
HI	harvest index
RY	crop residue yield (kg ha^{-1} yr^{-1})
IY	increased crop yield (kg ha^{-1} yr^{-1})
IRY	increased crop residue yield (kg ha^{-1} yr^{-1})
LHV	lower heating value (MJ kg^{-1})
HHV	higher heating value (MJ kg^{-1})

1. Introduction

The potential of biomass resources has been subject to increasing research and debate over the recent years. International and national agreements as the Kyoto Protocol [1] and EU Directives [2,3]; and policies as the European 20:20:20 Plan [4] and the US Recovery and Reinvestment Act [5] have put substantial pressure on politics promoting and sustaining the use of alternative energy carriers. The steep increase in oil prices in 2008 [6] further turned commercial attention towards alternative energy resources. The United Nations estimates that the current population of 6.9 Billion will increase to 9.1 Billion by 2050 [7], with increased demand for food, materials and energy as a consequence. The International Energy Agency estimates that energy consumption will increase with an expected 1.6% annual rate from 2005 to 2030 [8].

Biomass offers several options for displacing fossil resources [9–11]. An important question for policy and planning purposes is what amount of biomass resources is available. Several estimates of agricultural crop residue production or potential have been published in peer reviewed journals over the last 20 years providing different results. Estimates on global scale vary from 10 to 69 EJ yr^{-1} in 2050 [12–15], differences owing to different methodology and assumptions regarding residue production and ecological and economic availability of the resource. A common trait of many studies is the use of simple assumptions regarding residue production and ecological availability of agricultural residues. A number of studies apply scalar multipliers to crop production to estimate residue production [13,16–21], meaning that the amount of residue from a crop is assumed proportional to the total production of the crop, and not on the yield per area unit of the crop. A few apply function based multipliers [15,22,23], assuming that residue production is proportional to crop yield. The assessment regarding ecological and/or economic availability of crop residues tends to build on crude assumptions and often fixed scalar recovery rates used at national, regional or global level.

In this analysis we develop function based multipliers for estimating agricultural residue production based on crop yield. We apply the indicators on the global production of barley, maize, rice, soybean, sugar cane and wheat and estimate residue potentials for 22 geographical regions of the world. Also we estimate residue yields potentially achievable through agricultural intensification, and perform an analysis of the sensitivity of estimates.

2. Materials and methods

The assessment of agricultural production and residue potential builds on statistics from the Food and Agriculture Organization of the United Nations [24]. Harvested areas and crop yields are taken as averages over the three year period 2006–2008. The assessment covers all 227 countries and territories in the FAO database. Results are presented as aggregates into 22 geographical regions.

Six globally important crops in terms of production quantities are considered [24]; barley, maize, rice, soybean, sugar cane and wheat. Harvested area of these six crops covers 702 million ha corresponding to 50% of the world's arable land (1411 million ha) [24]. In FAO terms arable land include temporary crops (which covers the crops selected here), temporary meadows and pastures and fallow land. FAO does not provide a breakdown into these categories on a global level. Crop residues comprise straw from barley, rice, soy bean and wheat; stover from maize; and bagasse from sugar cane.

2.1. Theory/calculation

Residue production (RP) (kg yr^{-1}) for crop j in country i is calculated as:

$$\mathrm{RP}_{ij} = A_{ij} \cdot \mathrm{RY}_{ij}, \tag{1}$$

where A is harvested area and RY (kg yr^{-1}) residue yield by country and crop.

Residue yield is calculated from the residue to product ratio (RPR) for crop j. Empirical evidence suggests that RPR is not constant but proportional to yield (Y) (kg ha^{-1} yr^{-1}) [22,23,25]. Breeding in the 20th century has, specifically for cereals, increased the harvest index without significant changes in total biomass production [26] indicating an asymptotic development towards a theoretical limit determined by physiological constraints. This suggests an exponential relation between crop yield and residue yield, which is also shown by Scarlat et al. [23]. We assume a relation of the general form:

$$\mathrm{RPR}(Y) = ae^{bY}, \tag{2}$$

with residue yield calculated as:

$$\mathrm{RY}(Y) = Y \cdot ae^{bY}. \tag{3}$$

For $a > 0$ and $b < 0$ function (3) will, with increasing Y, decrease after a certain point and converge asymptotically toward zero. Such a development is not consistent with empirical evidence [27]. Residue yields tend to increase to a certain level with increasing crop yields and remain, in practice, constant hereafter. Building on the above assumptions we apply a piecewise continuous model for estimating residue yield as a function of crop yield for barley, maize, rice, soybean and wheat (see also Fig. 2):

$$\mathrm{RY}_{ij}(Y_{ij}) = \left\{ \begin{array}{c} Y_{ij} \cdot a_j e^{b_j Y_{ij}} \text{for } 0 \le Y_{ij} \le \frac{-1}{b_j} \\ \frac{-a_j}{b_j e} \text{for } Y_{ij} > \frac{-1}{b_j} \end{array} \right\} \forall a > 0,\ b < 0. \tag{4}$$

Yield experiments, probably also including measurements of residue production, are carried out in many countries by national agricultural extension services. Such data are, however, not readily accessible. Consequently we estimate parameters a and b in equation (2) on the basis of tabular data published in peer reviewed papers over the last 15–20 years (Table 1). The review has been limited to literature in English and data are evaluated as representing a fraction of published data. When RPR is not provided directly, RPR is calculated from harvest indices (HI) for each crop:

$$\mathrm{RPR} = \frac{1 - \mathrm{HI}}{\mathrm{HI}} = \frac{\mathrm{RY}}{Y}. \tag{5}$$

Harvest index is a measure of a plants partitioning of aboveground biomass into crop (grain) and other biomass. It expresses the weight of the crop relative to the total aboveground biomass

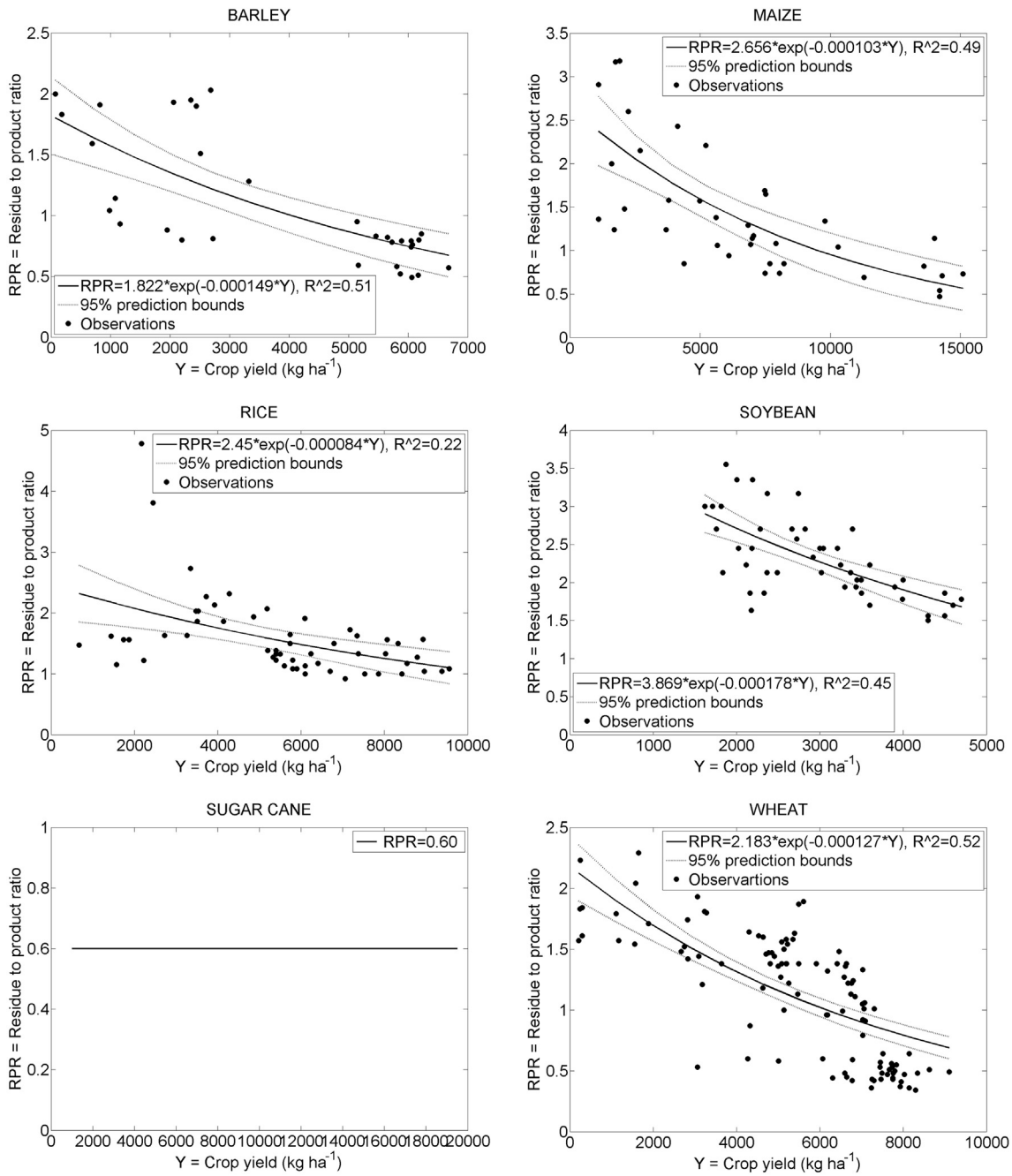

Fig. 1. RPR functions and 95% prediction bounds for the fitting function for barley, maize, rice, soybean, sugar cane and wheat. Due to the methodology applied to estimate the RPR function for sugar cane no confidence interval can be computed. Observations are based on references presented in Table 1.

[28]. Parameters and 95% prediction bounds of RPR functions are estimated with a non-linear least squares fitting algorithm in MatLab.

As a sterile plant, sugar cane differs from the other crops included in this analysis as the total biomass production is not partitioned between seeds and supportive tissues. Here we apply a constant RPR = 0.6 on dry weight basis in line with [29–31].

2.2. Physiological constraints

Plant physiology limits the range of residue to product ratios or harvest indices as the residue part of a crop provides physical support to the productive apparatus, mainly leaves, and to the crop itself [28]. A theoretical limit for harvest index for wheat is estimated to 0.60–0.65 (RPR = 0.67–0.54) [52,53]. In maize the harvest index has developed very moderately between the 1930s and 1980 suggesting a limit of ~0.55 (RPR = 0.82) [28]. Data from Khush [54] and Prasad et al. [55] suggest a harvest index limit for rice of ~0.60. The developed functions for estimating residue yield (4) and their parameterization (Fig. 1) do not violate the above described plant physiological constraints. A graphical representation of the model (4) developed here for estimating crop residue production and the ranges of crop reported yields used in the analysis are shown in Fig. 2.

Chrispeels and Sadava [56] report that average crop yield across a range of crops including barley, maize, wheat and soybean are 21.5% of maximum attainable yield. This yield gap can be caused by various factors as nutrient deficiency, water shortage, pests,

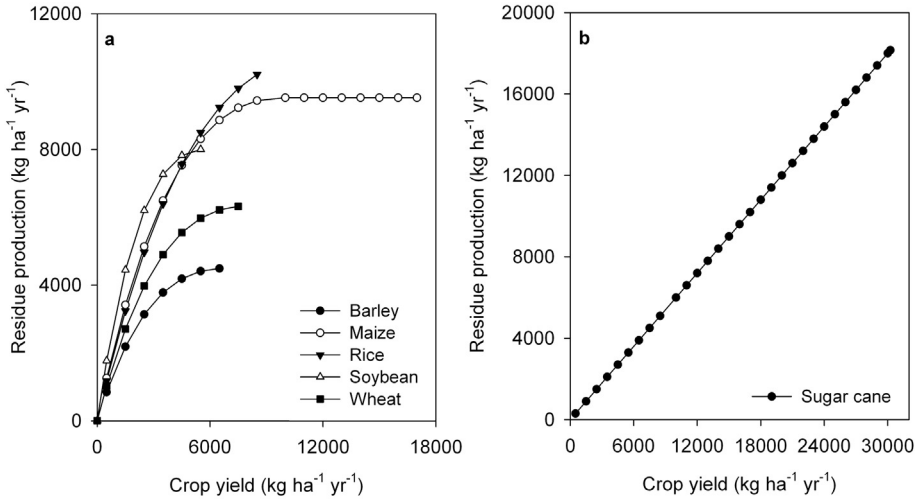

Fig. 2. Modeled relation between crop yield and residue yield for the six crops included in the analysis: barley, maize, rice, soybean and wheat in panel a, and sugar cane in panel b. The extension of individual curves represent the approximate range of crop yields reported by FAO (rounded to nearest 250 kg ha^{-1} yr^{-1}) and included in the analyses. The graph is based on the dry weight of crop and residue.

diseases or competition; either alone or in combinations. There is in many cases significant potential for increasing crop yields and consequently crop residue production. The potential for increasing residue production through agricultural intensification is estimated via a FAO/IIASA database on potential crop yields based on global agro-ecological zoning (GAEZ). Fischer et al. [57] provided estimates of availability of suitable land and crop yields for different levels of agronomic input. We apply a scenario for high input agricultural practices under rain fed conditions, thus providing an estimate of crop and residue production potentials, if every country had access to improved seeds, adequate fertilization and technology. As crop yield potentials we use estimates of average yield on the range of lands classified as very suitable to moderately suitable (VS-MS) if the potential amount of suitable land is bigger than the actual amount of land allocated to a specific crop. If not, we use yield estimates for the land suitability range very suitable to marginally suitable (VS-mS). For some country-crop combinations FAO/IIASA estimate a zero yield potential in contradiction with the FAOSTAT database on actual yields [24]. In that situation we assume that improved yield potentials equal reported current yields. The FAO/IIASA database includes 158 countries. For countries not included in the database we also assume that yield potentials equal current yields. The missing links between the FAOSTAT and FAO/IIASA databases is evaluated to have only marginal impact on the results. In mathematical terms, improved residue yield (IRY) (kg yr^{-1}) is estimated as:

Table 1
Data references used for parameterization of residue to product ratio functions.

	Location	Year(s)	No. of cultivars	Fertilizer application (kg N ha^{-1})	Crop type	Experimental design	No. of replicates	Ref.
Barley	Finland	1996–98	1	80,120	Spring	RCBD	3	[32]
	USA	1984–99	1	70	Spring	RCBD	4	[33]
	Denmark	1994–96			Winter/spring	Review of 416 measurements		[34]
Maize	Mexico	1975–93	64	0, 200	Landrace/improved	Review of 2 experiments		[35]
	Malawi	1997–99		95	Landrace/hybrid	RCBD	4	[35]
	USA, Spain, Germany	1920–98	9–189		Landrace/hybrid	Review of 9 experiments		[36]
	USA	1994–96	1	190–200		SP	4	[37]
Rice	India	1998–99	1	210	Hybrid	RCBD	3	[38]
	China	2000	118		RIL	RCBD	2	[39]
	China	2001	191		RIL	RCBD	2	[39]
	Thailand	1995	6	0, 30, 60		SP	4	[40,41]
	Bangladesh	1994–95	2	0, 90, 135		SP	4	[42]
	China	2005–07	2	150, 300	Hybrid	Review of 3 experiments	3–4	[43]
Soybean	USA	1992–93	1			RCBD	9	[44]
	Greece	1992–93	1	0, 120, 240		SP	4	[45]
	USA	1986–87	12			RCBD	3	[46]
Wheat	Finland	1996–98	1	80,120	Spring	RCBD	3	[32]
	Syria	1991–96	4	0, 100	Winter	SP	4	[47]
	China	2000–06			Winter	RCBD	4	[48]
	Brazil	1995	1	60		RCBD	5	[49]
	USA	1984–2004	2	70	Spring	RCBD	4	[33]
	Denmark	2008–09	10		Winter	RCBD	4	[50,51]

RIL = recombinant inbred lines, RCDB = randomized complete block design, SP = split plot designs.

$$\mathrm{IRY}_{ij} = \left\{ \begin{array}{c} IY_{ij,VS-MS} \cdot \mathrm{RPR}_j \text{ for } A_{ij,VS-MS} > A_{ij} \\ IY_{ij,VS-mS} \cdot \mathrm{RPR}_j \text{ for } A_{ij,VS-MS} \leq A_{ij} \\ Y_{ij} \cdot \mathrm{RPR}_j \text{ for } IY_{ij} \leq 0 \text{ or country not included in FAO/IIASA database} \end{array} \right\}, \quad (6)$$

Global production of plant components, cellulose, hemicellulose and lignin is based on data on composition of individual biomass fractions (Table 2). The composition of sugar cane bagasse and maize stover is based on average values from the US DoE Biomass Feedstock Composition and Property Database [58]. The composition of remaining residue species is based on average values from the Dutch Phyllis database [59]. Energy potential from agricultural residues is calculated as lower heating value (LHV) based on [59,60].

3. Results

3.1. Current residue production and energy potential

The current (2006–08) production of residues from barley, maize, rice, soybean, sugar cane and wheat is estimated to a total of $3.7^{+1.3}_{-1.0}$ *Pg* dry matter yr^{-1}. Maize, rice and wheat account for more than three quarters of the total production (Fig. 3).

Geographical regions standing out are North and South America, Eastern and Southern Asia with a residue production of more than 500 Tg yr^{-1} each. South-Eastern Asia and Eastern Europe have an estimated residue production of more than 200 Tg yr^{-1} each (Fig. 4, Table 2). The theoretical energy potential from the selected crop residues totals 65 EJ yr^{-1}. Geographically energy potentials range from zero in Polynesia and Micronesia to more than 11 EJ yr^{-1} in North America and Eastern Asia (Table 3). Polynesia and Micronesia fall out because their agricultural sector is focused on production of banana, cassava and coconut as their main commodities [24] and not cereals and pulses, which is covered in this analysis.

3.2. Current component production

The global production of cellulose, hemicellulose and lignin from barley, maize, rice, soy bean, sugar cane and wheat residues amounts to 1.376, 848 and 666 Tg yr^{-1} respectively (Fig. 5). Regions standing out are the same as above (North and South America, Eastern, South-Eastern and Southern Asia and Eastern Europe).

3.3. Additional residue production potential through agricultural intensification

Additional agricultural residue production is possible through development towards high input agriculture (Fig. 6, Table 4). High input meaning the use of improved seed sources, agricultural mechanization, mineral fertilizers and plant protection but, importantly, not through irrigation.

The total global potential of additional residue production is estimated to $1.3^{+1.0}_{-0.6}$ Pg yr^{-1} (dry matter). Particularly in South Asia there is a potential for increasing crop production and, consequently, residue production, but significant increases in crop and residue production could also be achieved in South East Asia and Eastern Europe (dominated by Russia).

4. Discussion

4.1. Residue production

Here we estimate the current (2006–08) total annual residue production from barley, maize, rice, soy bean, sugar cane and wheat to $3.7^{+1.3}_{-1.0}$ Pg yr^{-1}. Smil [53] estimated the total global production in the mid 1990's to between 3.5 and 4.0 Pg yr^{-1}, with cereals, sugar crops and oil crops accounting for 79% of the total production. Accordingly, the estimate by Smil for the crops included in this analysis would be in the approximate range 2.8–3.2 Pg yr^{-1}, which is lower than our estimate. A later study by Lal [61] estimates the global residue production to 3.4 Pg yr^{-1} in 1991 and 3.8 Pg yr^{-1} in 2001, with cereals accounting for 74–75% of the total and the six crops analyzed here accounting for 78–82%. With reference to year 2000, Krausmann et al. [62] estimate the global residue production to 4.4 Pg yr^{-1}. With the period 1997–2006 as a reference, Hakala et al. [63] find the global production of residues to 5.4 Pg yr^{-1}, i.e. considerably higher than other estimates and the one presented here. Hakala et al. build their estimate on crop specific harvest indices in contrast to residue to product ratios. Building on harvest indices results in higher estimates than residue to product ratios (see Section 4.4). Hakala et al. assume the harvestable part of the residues to be 71% of the total aboveground production yielding a production comparable to the above discussed literature of 3.8 Pg yr^{-1}. All figures discussed refer to the dry weight of biomass.

Wirsenius et al. [64] report the global residue production in energy terms. For the reference period 1992–94 they estimate the production to 61 EJ yr^{-1}, slightly lower than our estimate of 65 EJ yr^{-1}. However, their estimate is based on the higher heating value (HHV) of biomass, where ours is based on the lower heating value (LHV). HHV of biomass materials is typically 5–10% higher than LHV depending on the hydrogen content of the material.

There is a tendency, although not equivocal, that estimates of the global residue production depend on the applied reference year

Table 2
Moisture content, composition and heating value of crops and crop residues included in the analysis.

	MC crop	MC residue	Residue composition (dry weight basis)			LHV (MJ kg^{-1})	Ref.
			Cellulose	Hemicellulose	Lignin		
Crop							
Barley	0.15	0.15	0.46	0.23	0.16	18.2	[59]
Maize	0.15	0.15	0.35	0.23	0.19	17.9	[58,59]
Rice	0.15	0.15	0.36	0.24	0.16	17.5	[59]
Soy bean	0.15	0.15	0.40	0.16	0.16	17.7	[59,60]
Sugar cane (raw)	0.75	0.50	0.39	0.23	0.24	18.0	[58,59]
Wheat	0.15	0.15	0.38	0.27	0.18	18.2	[59]

MC = moisture content, LHV = lower heating value.

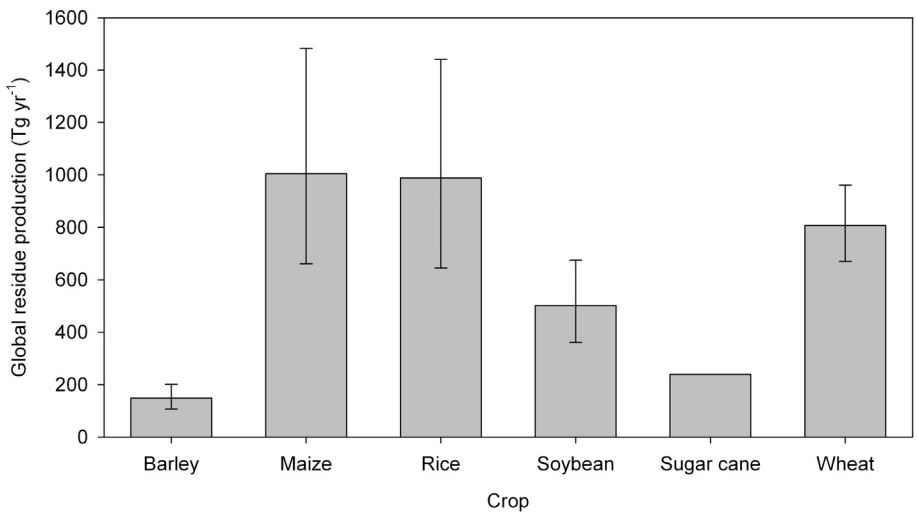

Fig. 3. Estimated annual global production of crop residue dry matter from barley, maize, soybean, sugar cane and wheat. Solid bars represent modeled values and error lines 95% confidence intervals. No confidence interval is attributed to sugar cane residue production due to the methodology applied; see Section 2.1.

(Fig. 7). Across the estimates reported by Smil [53], Krausmann et al. [62], Lal [61], Hakala et al. [63] there is an annual increase in residue production of ~1.5%. This corresponds well with the general increase in crop yields experienced, combined with a minor increase in the agricultural area harvested since 1990 [65]. These issues alone probably do not explain that our estimate is higher than earlier published estimates. The estimates by Smil [53], Krausmann et al. [62], Lal [61], Hakala et al. [63] and Wirsenius et al. [64] are based on crop specific scalar or geographically stratified crop specific scalar multipliers to crop yield in contrast to the methodological approach in this study.

4.2. Component production

72–86% of the residue resource is made up of carbohydrate (cellulose and hemicellulose) and phenolic polymers (lignin) (Table 2) each of which may substitute fossil resources. One option for carbohydrate processing is through biochemical conversion into ethanol [66] or other alcohols. Thermochemical conversion of carbohydrates produces hydrogen and carbon monoxide, which can be catalytically reformed to methanol. Fast pyrolysis and catalytic conversion of lignin may be used to produce phenol, styrene, benzene and toluene [9]. Task 42 of IEA Bioenergy estimate the global production of bio-based chemicals and polymers to ~50 million tons annually, and in recent years the market for a number of bio-based bulk chemicals has experienced a significant growth in the range of 10–30% annually [67].

4.3. Energy potential

The potential of bioenergy from agricultural residues has been estimated in a number of studies. For 2010, agricultural residue potentials are estimated to ~17 EJ yr^{-1} [68,69]. Smeets et al. [15] estimate the 2050 potential to 49–69 EJ yr^{-1}, which is corroborated by Haberl et al. [13] (49 EJ yr^{-1}). The Global Energy Assessment (GEA) [70] estimate the year 2005 energy potential from crop residues to 34 EJ yr^{-1} (technical potential) or 78 EJ yr^{-1} (theoretical potential). Corresponding figures for year 2050 are 49 and 107 EJ yr^{-1} respectively. The recent IPCC special report on renewable energy sources and climate change mitigation (SRREN) [71] finds a technical energy potential from agricultural residues of 15–70 EJ yr^{-1}.

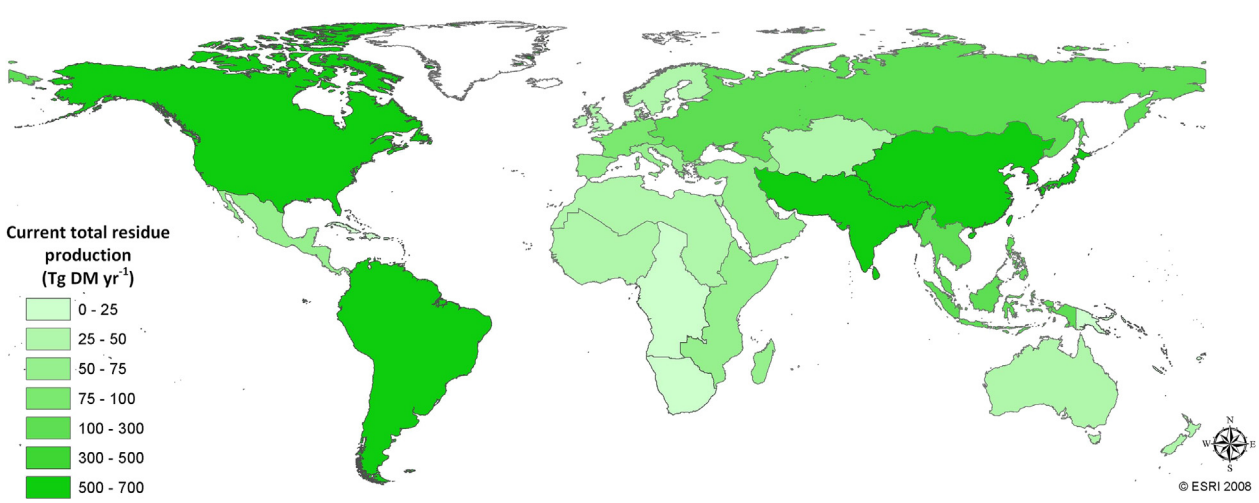

Fig. 4. Geographical distribution of estimated current (2006–08) production of residues from barley, maize, rice, soybean, sugar cane and wheat production.

Comparisons between energy potentials from different studies require caution as 'potential' can be defined in several ways [72,73]. The potential presented here is theoretical and thus comparable to the potential presented by GEA [70]. Assuming that our central estimate of 65 EJ yr^{-1} covers 80% of the total residue production, it is comparable to their estimate of 78 EJ yr^{-1}. Estimates of the technical, economical or ecological/sustainable energy potential all build on the theoretical potential, but are most often lower as various constraints on the exploitation rate are included in the models [73] (see Section 4.8).

The estimated theoretical energy potential from agricultural residues of 65 EJ corresponds to 15% of the current global energy consumption. A thorough review of the best use of crop residues is beyond the scope of this analysis, but opinions diverge. On one hand crop residues are considered a favorable feed-stock for ethanol production due to the relatively low lignin content [74] and low recalcitrance to bioconversion compared to more lignified material [75,76]. Fermentation of crop residues offers a relatively easy pathway to liquid fuels and to address GHG emissions and fuel supply security in the transport sector. On the other hand a pathway through combined heat and power production may be preferable as it offers higher GHG emission reductions than straw to ethanol or straw to Fischer-Tropsch liquids pathways [72]. The current (2010) energy use for transport is 99 EJ yr^{-1} [77] and is in the International Energy Agency's 2010 new policy outlook [78] estimated to increase to app. 190 EJ by 2035. Not only the best use of biomass for energy is debated, also bioenergy's potential for displacing fossil energy resources is questioned. A recent analysis by York [79] finds that additional production of renewable energy doesn't displace fossil energy in a 1:1 ratio. The results suggest that renewable energy resources tend to displace each other rather than the fossil resources they were intended to. However, the analysis is retrospective and doesn't inform about future developments in the energy supply.

4.4. Additional residue production

Agriculture offers two options for increasing the production of residues: intensification (producing more per unit of land) and/or expansion (producing on more units of land). Here we focus on intensification. The global potential increase in residue production is estimated to $1.3^{+1.0}_{-0.6}$ Pg yr^{-1}. Southern Asia exhibits a huge potential in increasing its residue production with close to 300 Tg yr^{-1}. Also Eastern Africa, South America, Eastern Asia and Eastern Europe exhibit potentials above 100 Tg yr^{-1}. In general it is the lesser developed regions of the world that has the largest unutilized potential, whereas North, South and West Europe respectively have limited options for increasing residue production through intensification, as also discussed by Haberl et al. [65].

The potential additional residue production estimated here does not refer to any particularly year, but implementing it would require significant efforts and developments in technology, agricultural practices and plant material, and hence time. Long term projections regarding biological production are sensitive to potential impacts of e.g. changing climates and diets.

Haberl et al. [65] model the impact on crop yield of climate change in 2050 and reach different conclusions depending on underlying assumptions. If the effect of elevated CO_2 levels in the atmosphere (CO_2 fertilization) can be fully exploited they find a yield increase in all regions with a global area weighted mean of +14.8% from 2000 to 2050. If CO_2 fertilization cannot be exploited, due to e.g. nutrient shortage, the global crop yield is modeled to decrease by 7.1%, with only Central Asia, Russia and Western Europe benefiting from climate change. For Europe, Olesen and Bindi [80] report similar findings, particularly that Northern European agriculture may benefit more from climate change than Southern Europe.

Dietary changes may also influence the production of agricultural residues as well as the availability of residues. Krausmann et al. [62] and Wirsenius [64] show that 65–70% of the biomass harvested from agricultural lands is used to feed and bed livestock. Also the Food and Agriculture Organization of the United Nations (FAO) find that livestock accounts for 70% of all agricultural land [81]. Changing diets may have counteracting effects on residue production and availability. On one hand reduced meat consumption reduces the demand for feed crops and thus the amount of crop residues. On the other hand it reduces the appropriation of crop residues for feed and bedding and, thus, increases the fraction of residues available for purposes other than for livestock. Haberl et al. [65] find that a switch to a "fair and frugal" diet increases the amount of crop residues available for energy purposes by more than 20% as compared to their business as usual scenario.

Our estimates of residue production through agricultural intensification build on modeling of attainable yields under rain fed conditions. Higher yield could be achieved through widespread use of irrigation. Much concern has, however, been raised over agricultural use of water resources [82]. The Aquastat database under FAO estimate that 70% of the world's fresh water use is accounted for by agriculture [83]. Regional variation is apparent. In Near East and North Africa agriculture use 51% of the renewable fresh water resource and 40% of this is used for irrigation. South Asia exhibits a significant draw on fresh water resources for agriculture and irrigation. In Latin America, irrigation accounts for 24% of water use by agriculture. Agriculture, however, withdraw only 1% of the renewable water resource. Applying a rain fed scenario to estimate potential residue production under high input agricultural practices thus provides a conservative estimate and may, for specific crops in specific regions, yield an estimate of attainable residue production lower than current residue production.

Tilman et al. [84] report that agricultural expansion required to feed the population in 2050 is additionally 890 million ha compared to year 2000. Pasture is expected to make up the majority. Smeets et al. [15] estimate potential expansion of agricultural land by 2050 in four scenarios to 729-3585 million ha; the latter including landless animal production and extensive use of irrigation. Much concern has also been raised over land use changes caused by agricultural expansion driven either by increased food demand or biofuel demand. It has been shown that fuel demand driven expansions may actually increase GHG emission [85] and introduce a carbon debt, which may take centuries to pay back depending on what kind of land is converted into agriculture [86,87]. The area needed to replace global consumption of oil with biofuels is estimated to be between 104 and 3142 million ha, depending on crop yield and the proportion of biomass converted to biofuel [88]. If 50% of a crop yield of 10 Mg ha^{-1} is converted 786 million ha is needed.

To the extent agricultural residues can be harvested without impairing soil quality and feed production, the land use impacts of an increased use of the resource must be expected to be only limited or absent (see also Section 4.8).

4.5. Development and use of multipliers

A variety of methodological approaches has been used to estimate crop residue production on national, regional or global scale. A majority of studies apply species specific constant multipliers to crop production statistics to calculate the residue production [13,16–21,53,61,63,64]. This means that residue production is assumed proportional to the total production of crops of different species (barley, wheat, rice etc.) in a given country, region or

Table 3
Estimated current (2006–08) annual production of crop residues in Tg (million tons) dry matter, and the theoretical energy potential from the residues. Missing numbers indicate values below 0.05.

	Africa					America				Asia
	Eastern-	Middle -	Northern-	Southern-	Western-	Caribbean	Central-	North-	South-	Central-
Barley (Tg)	**1.9**		**4.6**	**0.2**			**0.9**	**16**	**2.7**	**3.5**
Upper confidence limit	2.4		5.7	0.3			1.2	22	3.6	4.3
Lower confidence limit	1.5		3.6	0.2			0.6	11	1.9	2.7
Maize (Tg)	**37**	**6.2**	**7.7**	**15**	**25**	**1.2**	**46**	**309**	**125**	**1.8**
Upper confidence limit	47	7.7	12	20	32	1.5	61	511	174	2.5
Lower confidence limit	28	4.7	4.7	10	19	0.9	33	181	87	1.2
Rice (Tg)	**9.0**	**1.1**	**7.3**		**17**	**1.9**	**1.8**	**11**	**34**	**1.1**
Upper confidence limit	7.2	0.8	9.4		13	1.7	1.6	12	32	0.9
Lower confidence limit	6.4	0.8	3.9		12	1.3	1.2	6.2	22	0.7
Soybean (Tg)	**1.0**	**0.1**	**0.1**	**0.8**	**1.8**		**0.4**	**179**	**240**	**0.2**
Upper confidence limit	1.3	0.1	0.1	1.0	2.2		0.5	243	326	0.3
Lower confidence limit	0.8	0.1	0.0	0.6	1.4		0.3	127	171	0.2
Sugar cane (Tg)	**4.8**	**0.7**	**3.7**	**3.8**	**0.8**	**3.4**	**14**	**4.1**	**100**	
Wheat (Tg)	**4.9**		**20**	**2.9**	**0.1**		**3.9**	**114**	**29**	**36**
Upper confidence limit	5.6		24	3.4	0.1		4.8	133	34	42
Lower confidence limit	4.1		17	2.4	0.1		3.1	95	24	31
Total (Tg)	**58**	**8.0**	**44**	**22**	**45**	**6.5**	**68**	**632**	**530**	**43**
Upper confidence limit	68	9.3	55	28	48	6.6	84	926	668	50
Lower confidence limit	45	6.3	33	17	34	5.6	53	425	405	36
Theoretical energy potential (EJ)	**1.0**	**0.1**	**0.8**	**0.4**	**0.8**	**0.1**	**1.2**	**11.6**	**9.7**	**0.8**
Upper confidence limit	1.3	0.2	1.0	0.5	1.0	0.1	1.6	17.0	12.6	0.9
Lower confidence limit	0.8	0.1	0.6	0.3	0.6	0.1	1.0	7.8	7.4	0.6

globally. Krausmann et al. [62] add to the above assumption a geographical stratification of the species specific constant multipliers assuming that crop residue production not only is proportional to total crop production, but also to the location of crop production. A different approach is followed by e.g. Smeets et al. [15], Fischer et al. [22], and Bentsen et al. [89]. They build their estimates of crop residue production on species specific linear multipliers assuming that crop residue production is proportional to crop yield (production per area unit) rather than total crop production. A further development of this approach is demonstrated by Scarlat et al. [23] in their estimate of the European Union crop residue potential. They apply a species specific logarithmic multiplier to reported crop yields to calculate residue production. The methodological approach taken in this analysis is in line with that of Scarlat et al. but builds on considerably more observations and on physiological theory and on agricultural development showing that increased yield is caused not only by an increased biomass production but also by a change in biomass partitioning between crop and residue (increased harvest index) [28]. Scalar multipliers applied to crop yield may be adequate when looking at well-defined production systems as e.g. a specific crop in a specific climatic region. However, in a geographically and thus climatically and agronomically broader perspective scalar multipliers seem inadequate. Based on the present work we suggest that further development in crop residue assessments should focus on stratified species or cultivar specific exponential (or logarithmic) multipliers, with stratification based on ecological or political zones. Such an approach would require significantly more data than is readily available in the scientific literature but would be able to capture more of the variability caused by differences in climate, soil types, weather conditions or politically mandated restrictions e.g. on fertilizer use.

The model developed here predicts that crop residue yield increases logarithmically with increasing crop yield until a certain level of crop yield and remains constant with further increases in crop yield. The concave part of function (4) is parameterized via the references presented in Table 1 and there is sound empirical evidence for the relation between crop yield and residue yield in within the range of crop yields between 0 and $-1/b_j$ (see Fig. 1 for the crop specific parameter b). For crop yields exceeding $-1/b_j$, i.e. the horizontal part of the model, the empirical evidence is less solid. The influence of this model limitation on the results presented here is limited. The estimates of the current residue potentials are for more than 99.9% of the total residue production built on crop yield values between 0 and $-1/b_j$. Correspondingly for the estimates of potential additional residue production more than 99% of the modeled residue production build on crop yield values between 0 and $-1/b_j$. The results show that regions currently experiencing very high crop yields have limited potential of further increasing crop yields, while it is in the regions experiencing low and moderate yields that considerable increases could be expected. Although insignificant for the results presented here future crop residue assessments applying the methodology suggested here would benefit from further exploring the relation between crop yield and residue yield in very high yielding scenarios e.g. under assumptions of irrigation.

Using harvest index (HI) as a basis for calculating the residue to product ratio (RPR) may overestimate the ratio. Measured RPRs does not account for a proportion of biomass stored in stubble. Measured HI ideally includes this fraction as crops are harvested at soil surface level. The proportion of biomass stored in stubble is influenced by harvest technology. We have not applied corrections to data based on measured HI as the literature base behind our RPR functions do not provide information detailed enough to support specific assumptions. Hay [26] indicates that excluding stubble of 10 cm on tall and semi-dwarf varieties may induce a bias on HI of up to 5%.

Data from Pedersen [50,51] and Smil [53] suggest that variations in RPR cannot be attributed to crop yield alone. RPR varies not only between species in the same tribe as shown here for barley and wheat but also between cultivars of the same species [25]. Furthermore annual variations in RPR are found within cultivars on the same location, and also location itself is shown to influence RPR [25], indicating that residue production also depends on factors as soil type, weather conditions, fertilizer regimes (not only

Asia				Europe				Oceania			
Eastern-	South-Eastern-	Southern-	Western-	Eastern-	Northern-	Southern-	Western-	Australia and new Zealand	Melanesia	Micronesia	Polynesia
3.8		**5.8**	**12**	**46**	**13**	**13**	**17**	**7.7**			
5.3		7.4	16	60	19	18	27	9.6			
2.6		4.4	9.1	34	8.7	9.4	11	5.9			
225	**51**	**47**	**6.9**	**51**		**29**	**21**	**0.7**			
323	69	62	10	70		45	35	1.0			
150	36	34	4.5	35		18	12	0.4			
274	**285**	**338**	**1.5**	**1.3**		**3.3**	**0.1**	**0.4**			
284	256	290	1.5	1.2		3.4	0.1	0.5			
167	189	230	1.0	0.9		2.0	0.1	0.2			
39	**4.0**	**28**	**0.1**	**5.2**		**2.0**	**0.3**	**0.1**			
51	5.1	34	0.1	6.5		2.8	0.5	0.1			
30	3.1	21	0.1	4.0		1.4	0.2	0.1			
17	**22**	**60**						**5.4**	**0.5**		
125	**0.2**	**162**	**43**	**138**	**23**	**25**	**56**	**25**			
151	0.3	190	51	162	30	30	71	28			
101	0.2	136	37	116	18	21	43	21			
684	**362**	**640**	**64**	**241**	**36**	**73**	**95**	**39**	**0.5**	**3.6 E-04**	**4.6 E-04**
833	351	643	78	300	49	99	134	45	0.5	3.5 E−04	4.6 E−04
467	250	485	51	189	27	52	67	33	0.5	2.7 E−04	4.6 E−04
11.7	**5.8**	**10.8**	**1.2**	**4.4**	**0.7**	**1.3**	**1.7**	**0.7**	**9.9 E-03**	**6.0 E-06**	**8.8 E-06**
16.7	8.1	13.8	1.4	5.5	0.9	1.8	2.5	0.8	10.2E-03	7.6 E−06	8.8 E−06
8.1	4.1	8.3	0.9	3.5	0.5	0.9	1.2	0.6	9.6 E−03	4.6 E−06	8.8 E−06

quantities). Consequently the use of residue estimates based on crop yield should be restricted to generalized assessments of the scale of the resource; not to specific estimates of high resolution in space and time.

4.6. Uncertainty

Estimation of crop residue production and potentials is generally hampered by lack of information. Official statistics on agricultural residue production based on field measurements are only available to a very limited degree; hence the need for models to estimate the scale of the resource and consequently uncertainty of the estimates. The methodological approach taken in this analysis entails uncertainty in the parameterization of the relation between crop yield and residue production (3). Figs. 1, 2 and 4 and Tables 3–5 provides 95% confidence limits to the estimates of residue production and derived values of component production and energy potential. Particularly for maize and rice the estimated global production is associated with significant uncertainty, with upper confidence limit +46–48% and lower confidence limit -34-35% off the central estimate. Corresponding values for barley and soybean are +35–36% and −28%, and for wheat +19% and −17%. Uncertainty is also associated with residue production from sugar cane. However, with the approach taken in this analysis the uncertainty and thus confidence intervals cannot be estimated. We haven't found published empirical data on sugar cane residue production to support estimates of the uncertainty in the residue to product ratio.

Reduced uncertainty is desirable if estimates of agricultural residue production are to be used in industrial production planning. If agricultural residues are expected to play a larger role in future energy and material provision, it urgently calls for generally available statistics on residue production based on measurements in the field.

4.7. Current use of agricultural residues

Agricultural residues may have a multitude of functions in society [53]; either for nutrient recycling and soil amelioration (on-farm management), for bedding and feed, energy services or materials (on and off-farm). Very little information exists on how residues are actually used. Statistics from Denmark [90] show that allocation of the resource to different purposes varies even within the group of cereals (Table 5), which makes it questionable to apply general assumptions on residue use to a wider spectrum of agricultural residues and locations.

A number of modeling studies have estimated the use of crop residues. Krausmann et al. [62] find that out of a total production of 4.4 Tg yr^{-1}, 2.9 Tg (66%) is appropriated for various purposes (fodder, bedding and energy). They find considerable regional difference in the fraction of residue production harvested and used, from 29% in Sub-Saharan Africa to 90% in Western Europe. Also they find regional variation in the fraction of harvested residues allocated to feeding livestock from 10% or below in Europe and North America and Oceania to 83% in South and Central Asia. The fraction allocated to feed appear negatively correlated to the fraction harvested as might be expected. The findings by Krausmann et al. are corroborated by Rogner et al. [70] estimating the amount of agricultural residues harvested in 2000 to 54.3 EJ, corresponding to 2.9 Tg. A study by Wirsenius et al. [64] find on a global level that 41% of the total residue production is appropriated in the food system, i.e. as livestock feed. 29% is allocated to other purposes, e.g. energy, and 22% not harvested. The remainder is lost in distribution and storage. Regional variation in harvested fraction of the total residue production may be attributable to regional variation in crops grown. Lal [61] suggests that residues from cereals and sugar cane are the most suitable for harvest. If so, regions with a relatively high proportion of their agricultural area covered with cereals or sugar cane e.g. Europe and North America (regarding cereals) could potentially harvest a larger fraction of the total residue production. This assertion is supported by results from Krausmann et al. [62]. Significantly different assumptions are used by Fujino et al. [18] and Yamamoto et al. [21] in their assessment of global biomass resources. They assume that 0% of harvestable agricultural residues are used currently and therefore 100% of the resource is available for energy purposes.

The findings by Krausmann et al. [62] that up to 90% of the crop residues are used in Western Europe are not supported by

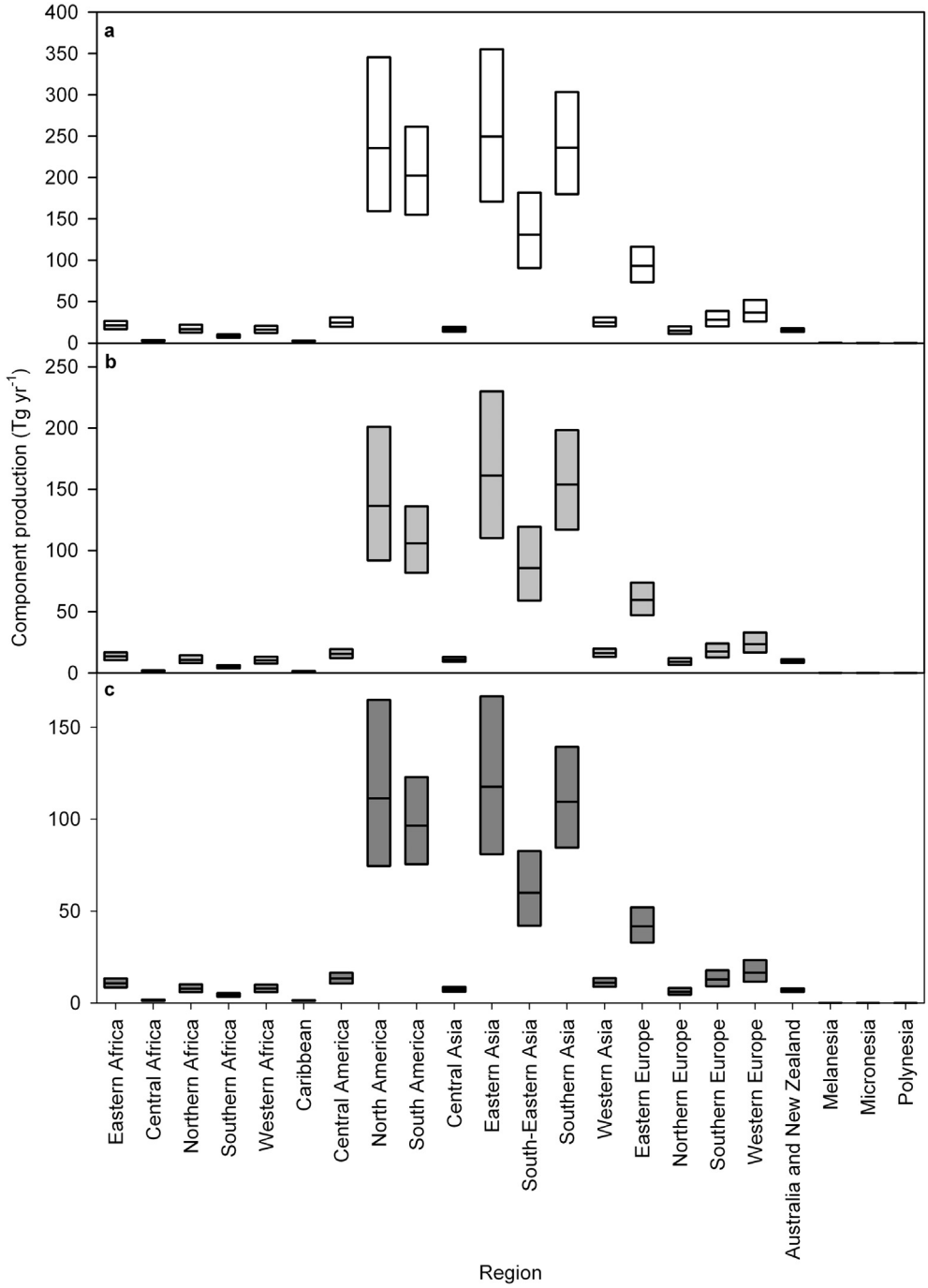

Fig. 5. Estimated current (2006–08) production of cellulose (panel a), hemicellulose (panel b) and lignin (panel c) from residues of barley, maize, rice, soybean, sugar cane and wheat.

other modeling studies and census reports. Weiser et al. [91] find for Germany that 24% of the harvestable cereal straw production is used for livestock husbandry and insignificant amounts used for energy purposes. On the European Union level, Scarlat et al. [23] find that between 1/5 to 1/3 of harvestable crop residues are used for livestock and little for energy. Similar assumptions (1/3 of harvestable residues used for livestock) are made by Ericsson et al. [16]. Denmark is one of few exceptions considering the use of agricultural residues in advanced energy supply [16,23], with 20–40% of the crop residues from cereal production used for energy (see Table 5). Still, only up to 60% of the total residue production is harvested and used for livestock or energy purposes [92]. For the US, the 'Billion ton annual supply study' [93] and its update [94] report an annual crop residue production of 550 million metric tons dry matter; a more recent study report the annual production to 518 Tg (= million metric tons) dry matter [95]. 5.6 million metric tons corn stover is used for energy corresponding to ~1% of the total production. The amount used for other purposes is not reported but the 'billion ton annual supply study' indicates use rates well below 20% of the total agricultural residue production.

Across modeling studies and national statistics a total global human appropriation of crop residues of 40–70% appears, however, with considerable variation between crops, regions and purposes.

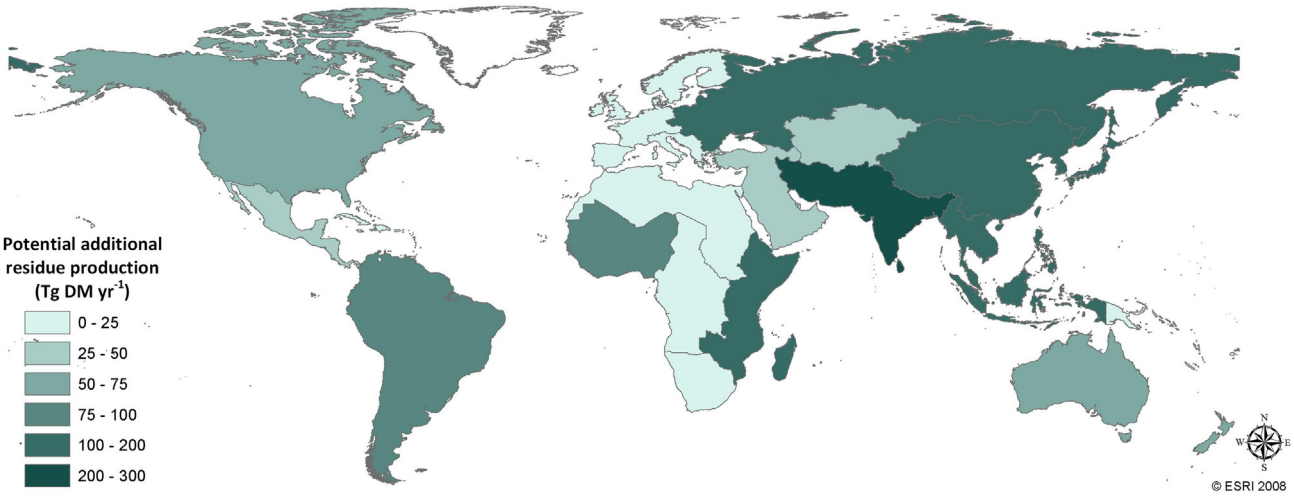

Fig. 6. Geographical distribution of potential additional residue production attainable through agricultural intensification.

4.8. Resource availability

The results presented here provide an estimate of the amount of crop residues theoretically available from agricultural land that is harvested. Thus we present an upper limit of the amount of crop residues to support energy, material and agronomic services. The amount of residue available ecologically or economically is a fraction hereof.

Crop residues offer a number of benefits to soil quality, carbon sequestration, erosion control and crop yields. Particularly on degraded soils residue retention is beneficial, but removal has an impact on soil quality in all regions and climates, although much higher in tropical than temperate climates [96,97]. Removal of crop residues in tropical and temperate semi-arid climates tends to decrease carbon content in soil. Similar practice in cold and humid climates does not have the same effect on soil carbon [98]. A positive correlation between carbon content in soil and soil productivity is demonstrated for various crops in different regions [97,99–103]. On the other hand it is shown that differences in crop yield induced by differences in soil organic carbon (SOC) content in many cases can be overcome by appropriate supply of mineral fertilizers [104,105] unless differences in soil organic carbon content are substantial [104]. Recycling of by-products from biomass conversion is an option to mitigate the negative effects of biomass extraction. Ash recycling from biomass combustion can return a fraction of primarily the phosphorous and potassium extracted from the soil. The char fraction from gasified or pyrolyzed biomass furthermore contain a fraction of the carbon extracted with the biomass in a more stable form.

The complexity of residue removal, soil organic carbon and crop yield interactions restrict specific estimates of sustainable (from an SOC point of view) recovery rates to compartment, field or subfield levels [100,106], disabling meaningful estimates at the geographical scale used here. In general, sustainable recovery rates correlates positively with soil organic carbon content and negatively with temperature and aridity. Regions characterized by low SOC soils ($<$18 t ha^{-1} SOC) are Western, Northern and South Africa; Western and Central Asia; Australia; southern part of South America and parts of mid-west US [107]. Arid climates according to the Köeppen-Geiger classification are found in some of the same regions; Northern, Western and parts of Southern Africa; Western and parts of Central Asia; Central US, Mexico and South-Central South America [108]. Literature presents sustainable recovery rates of agricultural residues between nothing [109] and everything [110],

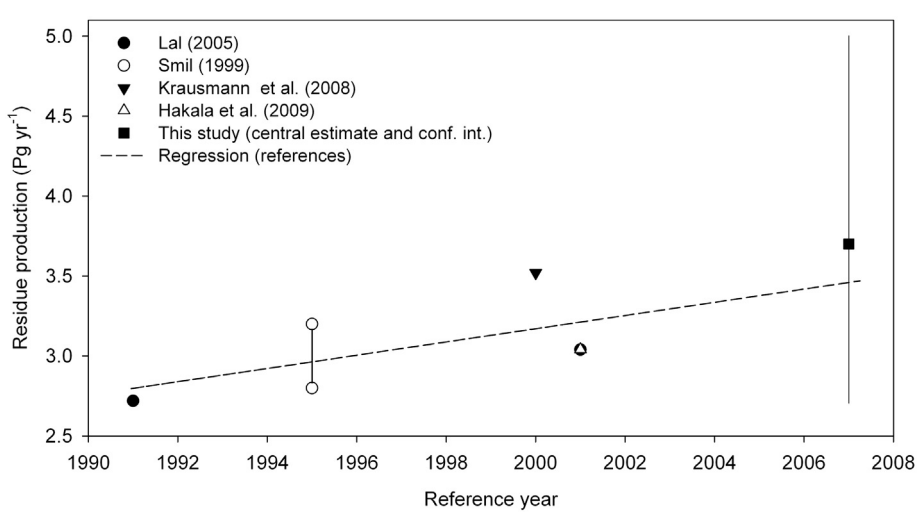

Fig. 7. Estimates of the global agricultural residue production from cereals and sugar cane relative to the reference year applied in different studies. Reference data from Lal [61], Smil [53], Krausmann et al. [62], and Hakala et al. [63]. For comparability estimates by Krausmann et al. and Hakala have been multiplied by 0.80 under the assumption that this study cover 80% of the total global residue production, which they report.

Table 4
Potential additional annual production of crop residue dry matter, which is realizable through agricultural intensification. Quantities in Tg (million tons) dry matter per year. Missing numbers indicate values below 0.05.

	Africa					America			
	Eastern-	Middle -	Northern-	Southern-	Western-	Caribbean	Central-	North-	South-
Barley	**2.4**		**10**	**0.1**			**0.4**	**6.0**	**1.4**
Upper confidence limit	4.0		16	0.2			0.7	14	2.6
Lower confidence limit	1.3		6.2	0.0			0.2	1.9	0.7
Maize	**87**	**14**	**0.4**	**10**	**48**	**2.8**	**38**		**61**
Upper confidence limit	160	26	0.7	19	92	4.6	76		130
Lower confidence limit	45	7.8	0.2	4.6	23	1.6	16		23
Rice	**9.4**	**0.9**			**27**	**0.9**	**0.9**		**8.9**
Upper confidence limit	16	1.5			45	1.7	1.8		17
Lower confidence limit	5.2	0.5			16	0.4	0.4		3.9
Soybean	**1.1**	**0.1**		**0.4**	**2.4**		**0.1**	**2.0**	**11**
Upper confidence limit	1.6	0.1		0.6	3.6		0.2	3.4	20
Lower confidence limit	0.7	0.0		0.2	1.5		0.1	1.1	5.9
Sugar cane	**2.0**	**1.6**		**0.8**	**0.6**	**2.9**	**0.8**		**1.0**
Wheat	**5.0**		**18**	**1.3**	**0.1**		**0.1**	**73**	**19**
Upper confidence limit	6.7		24	1.7	0.2		0.1	109	26
Lower confidence limit	3.7		14	0.9	0.1		0.1	46	13
Total	**107**	**17**	**29**	**12**	**79**	**6.6**	**40**	**81**	**103**
Upper confidence limit	190	29	41	22	142	9.2	80	127	197
Lower confidence limit	58	9.9	20	6.5	41	4.9	18	49	48

with a trend towards recovery rates of general validity for the crops included here between 25 and 60% [16,19,21–23,111,112]. Specific thresholds require that models are refined to include the site specificity of crop and soil interactions [100].

In this study, we show that there are considerable biomass resources that are technically and, most likely, also ecologically available among agricultural residues. It is an open question, however, how much of these resources can be considered economically available or relevant. There is a large and growing international trade in wood residues for fuel and refineries, which dwarfs the corresponding international trade in other agricultural biomass residues for fuel and refineries [113–115]. Agricultural biomass residues for energy purposes appear to be mainly traded locally or regionally in the nations states. Indeed, in e.g. Denmark and other European countries, large amounts of straw deliveries are contracted each year for the local combined heat and power plants. Part of the explanation for this pattern, and the difference to the market for wood residues, is undoubtedly found in the differences in production system and hence cost of making these resources economically available and relevant for the energy sector internationally e.g. seasonal variability for agricultural residues and the ability of wood to be stored at the stump for years at low or even negative costs. For the biomass resources in agricultural residues to be truly economically relevant for the energy sector, locally, regionally and internationally, these challenges must be solved by the market agents to a degree that the resource can compete with alternatives. Increased demand for biomass of all forms for the bioenergy and refinery sectors will of course in itself make more of these resources economically relevant as relative prices increase. In turn, this should increase the incentive for investing in the development of new technologies to remedy and reduce the above challenges and cost elements.

Table 5
Relative allocation of barley and wheat straw to different purposes in Denmark. Average values for 2006–2008 based on [90].

	Barley	Wheat
Energy	20%	38%
Feed	40%	12%
Bedding	16%	11%
Not harvested	24%	38%

4.9. Other biomass resources

Global terrestrial net primary production (NPP) aboveground is estimated to 33.54 Pg yr^{-1} of carbon [116]. With an average carbon content of biomass of 45–50% [117] this corresponds to 67–74 Pg (billion tons) of dry biomass. Annual human appropriation of aboveground terrestrial biomass (HANPP) is estimated to 10.2 Pg carbon corresponding to 29% of NPP [116].

In light of global NPP and HANPP production of agricultural residues is a marginal fraction. It may be argued that the human appropriation of crop residues equals production as; no matter how residues are used they have a function in society, be it feed/fodder, building material, fuel, soil amelioration, erosion prevention etc. Forests are estimated to account for 48% of terrestrial NPP compared to 14% from cultivation [118] and forests are seen as one of the major potential suppliers of biomass for energy and material services [12,21,119]. Many studies point to energy crops on abandoned agricultural land as being the biggest resource of future biomass supply for energy [15,16,21,68,120–123], with major regional variation.

5. Conclusions

In this paper we developed a model to estimate the production of crop residues from six globally important crops. The model is based on an exponential relation between crop yield and residue production, and represents a methodological development that to a higher degree is based on crop physiology and empirical evidence from a range of agricultural experiments.

In applying the model on crop yields averaged from 2006 to 08 we find the global production of crop residues from barley, maize, rice, soybean, sugar cane and wheat to $3.7^{+1.3}_{-1.0}$ Pg dry matter yr^{-1}. Ecological and economic availability of agricultural residues is not determined specifically but substantial amounts of biomass are probably available on short term from land areas already under some level of agricultural management. This may reduce the

Asia					Europe				Oceania			
Central-	Eastern-	South-Eastern-	Southern-	Western-	Eastern-	Northern-	Southern-	Western-	Australia and new Zealand	Melanesia	Micronesia	Polynesia
3.8	**1.0**		**4.7**	**14**	**31**	**2.4**	**4.6**	**0.7**	**11**			
5.8	2.6		7.9	26	69	8.0	11	6.1	20			
2.4	0.3		2.5	7.2	13	0.7	1.5	0.0	6.0			
	48	**17**	**52**	**0.8**	**14**		**1.7**		**0.1**			
	114	31	104	1.7	24		3.8		0.3			
	14	8.6	24	0.3	6.8		0.6		0.0			
	15	**102**	**145**									
	36	195	275									
	4.6	46	67									
	21	**2.1**	**29**		**4.8**		**0.1**					
	33	3.1	44		7.5		0.1					
	12	1.3	18		2.9		0.0					
	0.2	**0.9**	**1.9**							**0.3**		
29	**22**	**0.2**	**37**	**34**	**98**	**2.1**	**11**	**2.3**	**49**			
36	36	0.3	48	48	143	4.2	17	7.4	65			
23	12	0.2	28	24	65	1.0	6.5	0.4	37			
33	**107**	**122**	**269**	**49**	**148**	**4.5**	**17**	**3.0**	**61**	**0.4**		
42	222	230	481	76	245	12	32	14	85	0.4		
26	43	57	142	31	88	1.7	8.7	0.4	43	0.3		

impacts from land use change if or when the biomass is harvested and used for energy or material purposes displacing fossil resources.

There is considerable geographic variation in the production of agricultural residues, and also in ecological constraints for recovering these residues. Regions where particular attention on sustainability is required are Western, Northern and South Africa; Western and Central Asia and South-Central South America.

Most regions of the world have a potential for increasing the production of agricultural residues through development towards high input agricultural management. As a global total we estimate the additional potential to $1.3^{+1.0}_{-0.6}$ Pg yr^{-1}. Northern, Western and Southern Europe already apply high input agriculture and have little potential for increasing residue production. Over time, changing climates and diets may influence the potential for increased residue production and may counteract as well as support increased production.

Lack of available data on agricultural residue production is a significant barrier for the development of accurate models on residue production. If agricultural residues are expected to play a larger role in future energy and material provision, reliable statistics are needed.

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